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SOIL-SHEET PILE INTERACTION - PART II: NUMERICAL ANALYSIS AND SIMULATION

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ABSTRACT

This study investigates the interaction between soil and the embedded sheet pile wall at the interface which is not generally well captured in the conventional theoretical and design methods. This was implemented by carrying out numerical analysis to study the behavior and response of the two contacting materials using incremental loading technique. The effects of the interaction were investigated in terms of deformations and stress distributions, all based on Finite Element technique. Numerical analyses of sheet pile wall embedded in homogenous and heterogeneous soil strata were performedindependently. The results showed variation between the theoretical conventional design approach and that of the numerical analysis for both anchored and cantilevered sheet pile walls. The numerical analysis showed various cases of overestimation of deformation in assumed homogenous sand by 31.28% compared to the ideal heterogeneous soil layers, with strong indication of the positive contributions of cohesion values in soils generally assumed as cohessionless. Additional study on the possible replacement of embedded conventional steel rebar with Carbon Fibre Reinforced Polymer (CFRP) in concrete sheet pile along corrosive shoreline environment was undertaken. The general response of the CFRP reinforced pile in relation to conventional steel showed no significant variation in terms of horizontal deformation.

Keyword: Numerical, Homogeneous, Heterogeneous, Soil, Sheet-pile

1.0 INTRODUCTION

In an accompanying paper (Olubanwo and Ebo, 2015), a review on the theories and design methods of the interaction between soil and embedded sheet pile wall was presented. As seen, while useful conclusions were drawn from the review, it was not possible to quantify such conclusions in numerical terms. This will be implemented in this paper by employing numerical methods. The numerical work in this case was designed to obtain all necessary results required for adequatesimulations and description of the responses of the deformed configurations of embedded RC concrete sheet pile in soil.

Sheet pile walls are popular civil engineering structures widely used as earth retaining and support system for excavations, waterfront structures, cut-off walls, cofferdams, flood walls etc. to provide lateral earth support. Sheet pile walls can be either anchored or cantilevered depending on various conditions such as embedded soil type, wall height etc. (Ömer, 2012).

Sheet pile walls can be cantilevered for less heights of about 3 to 4.5m or anchored for higher heights for provision of support against tripping or fall due to lateral pressure and forces from retained soil, surcharge load etc. (USACE, 1996).

Conventional design of sheet pile wall is based on limit equilibrium assumptions made up of free and free earth support method with the free earth support method predominantly in use due to simplicity in its approach. This conventional method of design utilises the active and passive earth pressures acting on the sheet pile wall with the failure criterion based on Mohr-Coulomb criterion.

The use of conventional method in design of structures like foundations, slope stability, retaining walls etc. are associated with various shortcomings. However, the use of numerical modeling takes into consideration some of those areas which the conventional method fails to accommodate. For instance, in design of soil retaining structures such as sheet pile walls, the conventional method takes into consideration the design for both internal and external stability, overturning, sliding etc but fails to study the interaction between the structure and backfill e.g soil, the effect on adjacent structures, construction stages, deformation, comparison with field data etc. all of which can be considered in numerical technique. Hence, the use of the numerical method gives a more ideal solution and design output and generally acts as an advanced approach which has the ability of taking more variables into consideration (Laszlo 2006).

This paper among other things investigates some aspects of theoretical modelling assumptions which do not reflect the true behaviour of soil-sheet pile structure, which generally results in over-conservativeness in design, leading to quandary, uncertainty in accuracy of results and varying results for a particular design all of which are detrimental to both the design engineer and the project in general.

2.0 NUMERICAL ANALYSIS, METHODOLOGY AND PROCEDURES

Prior to carrying out the numerical study, considerations were given to some inherent challenges associated with the application of FEM and ways of mitigating the challenges were also implemented, these include:

- Modeling and discretization of the geometry - guidelines for description of the geometry problems which includes the number of nodes, mesh size etc. were established.
- Modeling of various constituents and selection of parameters - evaluating the need to incorporate some level of advancement and complexity.
- Speculative difficulties in computation with comparison and exploitation of various ways of achieving the objectives.
- Obtaining the design output: trying to understand what has happened and observation of deviation from expected result e.g. out-of-balance deformation, abnormal stress distribution etc.

This study uses results of soil investigation data which include Soil Penetration Test (SPT) and laboratory tests results obtained from an on-going sheet pile project at Onne Port development in Rivers State, Nigeria. The SPT and soil data are shown in Table 1.

Table 2.1: Soil properties and parameters

S/N	Depth range (m)	Description	Cohesion (kN/m^3)	Angle of internal resistance (^{o})	Unit weight, γ (kN/m^3)
1	0 – 2	Organic sand	0	38	16.19
2	2 – 8	Soft clay/clayey sand	5	27	19.05
3	8 – 14	Soft to firm silty sand	1	36	21.98
4	14 – 22	Clay/clayey sand	6	30	17.9
5	22 – 26	Fine grained sand	0	37	21.75
6	26 – 35	Medium grained sand	0	39	21.86

2.1 Method of analysis

The analysis method comprised geometric modeling of the soil and embedded sheet pile wall using ANSYS FEM code, which allows complicated nonlinear soil behaviour with various interface constitutive laws.

2.1.1 Soil - Sheet pile FEM Modelling

A two-dimensional plane strain FE model was implementedin each investigation using ANSYS FEM code. For the anchored configuration, a 12m length of sheet pile with an embedment depth of 4m in the soil was considered. Hence, the retained height was 8m with anchorage at 1m below ground surface. For the cantilevered configuration, an 18.2m with embedment depth of 10.2m was considered based on theoretical estimate.

The reinforced concrete sheet pile wall which is a composite of concrete and reinforcements was transformed into a homogenous material applying the transformed section technique. Several models comprising of both anchored and cantilevered wall were modelled with conventional steel and CFRP reinforcements independently for idealised homogenous and stratified soil layers.

The procedures for determining the required embedment and total depth of the sheet pile for both cantilevered and anchored follows the current practice for homogenous sand and is the current practice in sheet pile design using the free earth support method described by limiting equilibrium assumptions given in EuroCode 7 (BS EN 1997) and British Standard 8002 (BS 8002:1994); where both serviceability and ultimate limit state conditions were considered.

2.1.2 Geometry and boundary conditions

The modelled cantilevered and anchored sheet pile walls are shown in Figures 1.

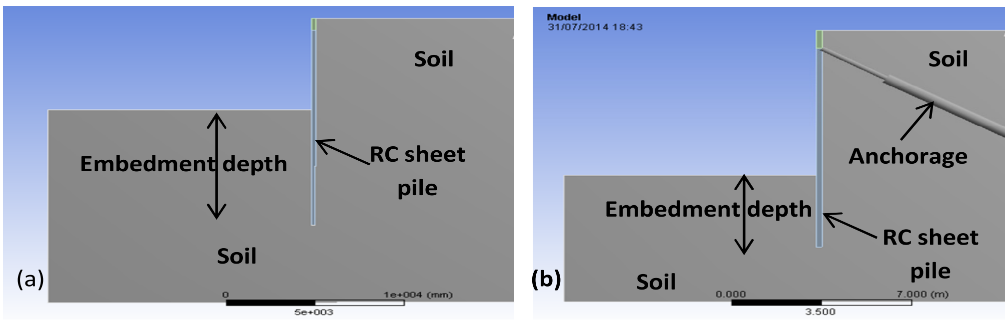


Figure 2.1: (a) Cantilevered sheet pile model (b) Anchored sheet pile model

The modelled soil and sheet pile was properly meshed with finer mesh at the soil-wall contact region which is the main area of interest with boundary conditions which include restraint in the x-direction along the soil depth and fully fixed at the base area of the soil. This was in close relation to the ideal site condition displaying the nature and behaviour of soil.

2.1.3 Nonlinearity Modeling

For the modeling of the soil and sheet pile wall, three kinds of nonlinearities associated with the soil and concrete materials were considered, these includes;

- Geometric nonlinearity as a result of the large deflection and strain, stress stiffening of the both members.
- Material nonlinearity due to the creeping and plasticity of the materials. The sheet pile concrete was modelled as a homogeneous isotropic nonlinear inelastic material. The Drucker Prager model selected for the soil model accounted for the material behaviour as its plasticity is applicable to the granular soil and accounting for its friction especially at the interface.
- Nonlinearity of the contact between the soil and sheet pile wall as a result of changing status.

Considering the above nonlinearities associated with the model, the Drucker-Prager model which is a simplified and modified von Mises model and frequently applied in most practical cases with the material constants was used due to the following advantages:

- Simple criterion for failure having most of its parameters obtainable from normal triaxial tests.
- Has a smooth surface failure and convenient to use mathematically.
- Takes account of hydrostatic pressure and gives good result as traces of its failure surface on the meridian planes are straight lines which gives room for expectance of reasonable result.
- It takes into consideration the influence of intermediate principle stress unlike the Mohr-Coulomb criterion.

In terms of contact and interaction modelling, the soil and sheet pile wall are initially in contact with each other, as the two surfaces touch each other they possess the following characteristics;

- They become mutually tangent.
- Do not penetrate into each other.
- Both compressive normal forces and tangential friction forces can be transferred along the two entities.
- They are free to separate and move away from each other.

The interface contact model was introduced using frictional contact option by specifying the TARGET and CONTACT between the members under consideration i.e soil and sheet pile, with the sheet pile wall with higher stiffness value being the target and the soil as the contact. The contact model involved specifying some relevant data to account for the contact behaviour which includes; coefficient of friction, penetration tolerance, pinball region etc with relevant values as contained in Table 2.

Table 2.2: Input data for various materials

S/N		SOIL	CONCRETE	STEEL	CFRP
1	Elastic Modulus	20N/mm^2	30,000N/mm^2	210,000N/mm^2	230,000N/mm^2
2	Poison ratio	0.3	0.2	0.3	0.26
3	Coefficient of friction between concrete and soil		0.3		
	TRANSFORMED STEEL AND CONCRETE COMPOSITE			TRANSFORMED CFRP AND CONCRETE COMPOSITE	
4	Elastic Modulus	147,000N/mm^2		160,000N/mm^2	
5	Poison ratio	0.27		0.24	

The compatibility at the interface is important so as to capture the separation of the sheet pile and soil away from each other during loading. This was achieved by excluding penetration, though a tolerance of 0.1mm was allowed to account for roughness and interaction at the interface. The anchor was bonded to the sheet pile and fixed to the soil which is same as in practice.

2.1.4 Convergence and solution

Obtaining convergence is one of the key challenges associated with nonlinear FEA; this is a function of the input data, load pattern and general behaviour of the model. For obtaining a converged solution, the solution must start within the radius of convergence. This is unknown but through initial trials better converged solutions were obtained. Incremental load pattern was employed to the analysis taking a step-loading approach to carter for the nonlinearity at different sub-steps so as to obtain converged and verifiable results. The incremental load pattern is as shown graphically in Figure 2.2.

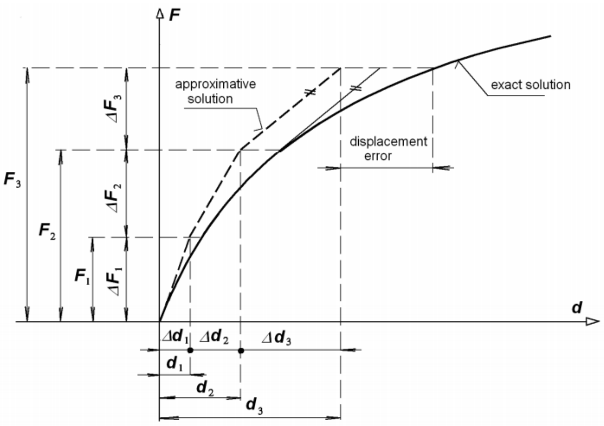


Figure 2.2: Incremental loading pattern of the model(Ivančo 2011)

As shown in Figure 2.3, the solution of the model shows a progressive exactness. This is typical of the solver used for the model i.e. Newton-Raphson method which runs iteration of the converged solution using the relation:

$$[K^T]\{\Delta d\} = \{F\} - \{F^{nr}\} \qquad 2.1$$

Where $\{\Delta d\}$ = nodal displacement change.

$\{F\} - \{F^{nr}\}$ = residual/force imbalance.

In carrying out this based on the above criterion, the solution continues until residual, $\{F\} - \{F^{nr}\}$ reduces to a very small value up till the force convergence criterion thereby meeting the condition; residual < criterion i.e $\|\{R\}\|_1 < (\varepsilon_R R_{ref})$, the solution is then converged (ANSYS 2010).

3.0 RESULTS ANALYSIS AND DISCUSSIONS

The analysis of results obtained are carried out in regard to the active and passive earth pressures with plots showing the deformed shapes, stress and strain distribution of the soil and sheet pile obtained from the FEA. The results obtained from both the anchored and cantilevered sheet pile include that from assumed homogenous sandy soil and the model containing the different soil strata and properties.

3.1 Cantilever Sheet Pile Wall

Stability of cantilevered sheet pile walls are dependent mainly on the depth of penetration/embeddment into the soil. Generally, the provision of adequate penetration depth which helps to limit the extent of deformation of the wall forms the basis of conventional design which uses limit equilibrum principle,and it's assumed fixed at the toe as shown in Figure 3.1.

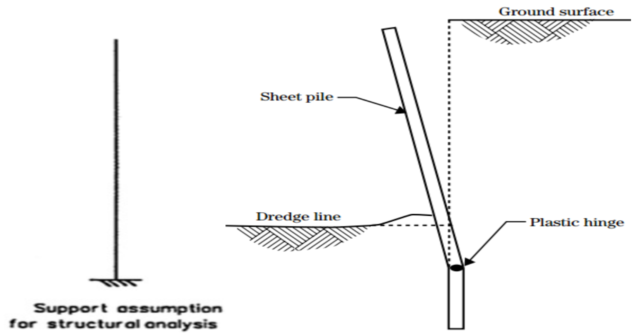


Figure 3.1: Assumed Support and failure for cantilevered sheet pile wall (Technical Supplement 14R 2007)

3.1.1 Cantilever sheet pile in Homogenous Sand

Conventional design of cantilever sheet pile walls based on limit equilibrum method takes into consideration the failure mode of the wall under loading by examining the forward rotation of the wall due to inadequate passive resistance. Stability of the wall is achievable from the passive resistance which are mobilised on the portion of the wall embedded to the soil. This includes assumptions that the wall failure mode involves rotation of the wall at a point just above the toe with accompanied passive pressure developed above the point of rotation.

This is true with the FE modeling and analysis carried out in this study. The horizontal displacements or deformations for test specimentsreinforced with steel rebar and CFRP rae given in Figure 3.2.

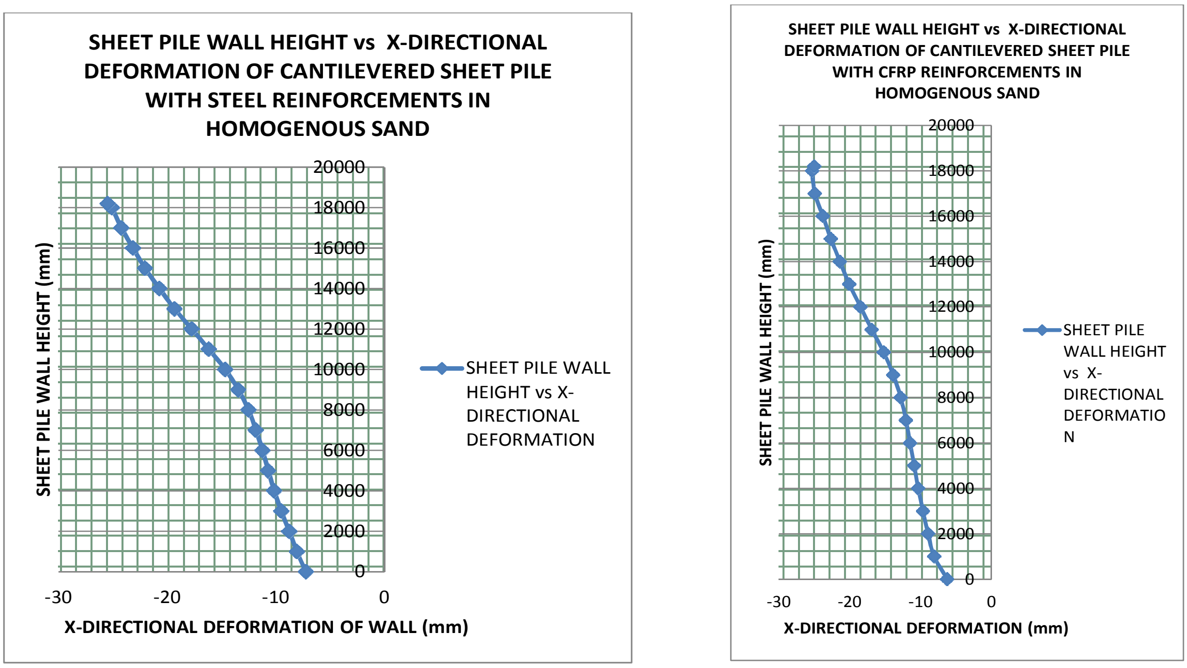


Figure 3.2: Horizontal deformation of wall with Steel& CFRP

In addition to the rotational movement in the horizontal direction as shown indicated earlier, translational motion of 7mm and 6mm in the direction of the passive side the soil was observed about the toe of the wall for steel and CFRP reinforcements respectively.This is illustrated in Figure 3.2. Such phenomenon istypically ingored and cannot easily be detected in the conventional limit equilibrum design approach.

3.1.2 Cantilever sheet pile in Heterogeneous Soil

Similar translational movement of about 12mm and 2mm for wall reinforced with steel and CFRP respectively was observed. This follows an irregular deformation pattern unlike the smooth curved deformation assumed in conventional designapproach. This is illustrated in Figure 3.3.

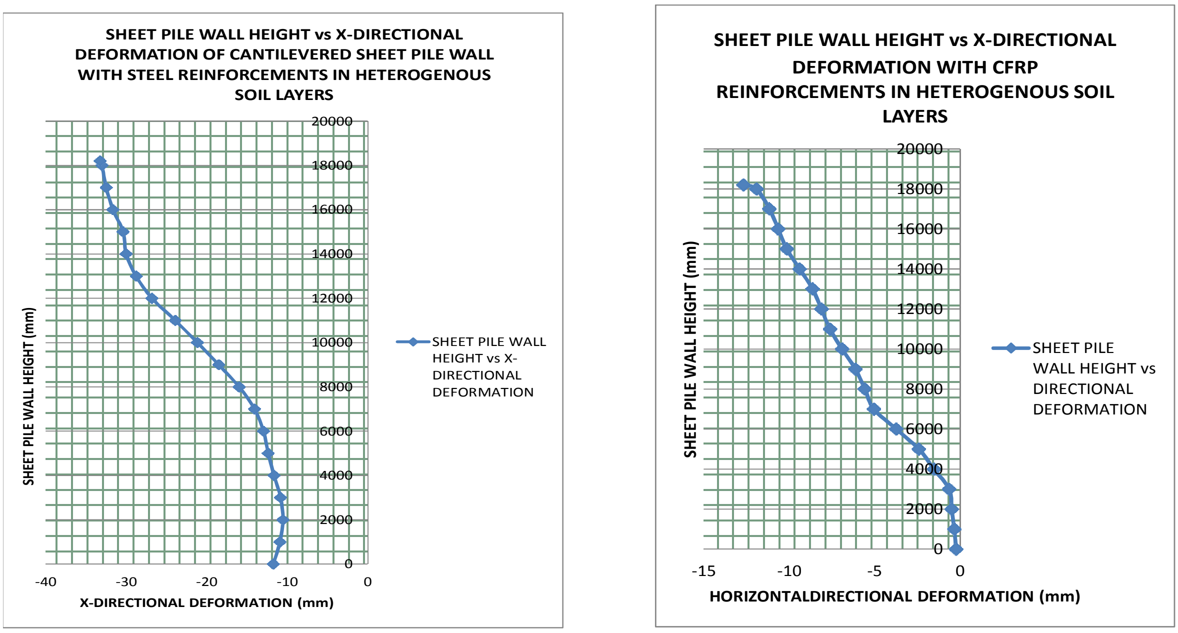


Figure 3.3: Horizontal deformation of cantilever wall with steel& CFRP

3.2 Anchored Sheet Pile Wall

For the anchored wall, anchores were provided to reduce the depth of embedment with the support assumptions shown in Figures 3.4. The free-earth support method used in this study is based on the assumption that the stiffness of the sheet pile wall is much higher than that of the soil with insufficient embedment to avoid rotation of the wall despite the wall is in equilibrum.

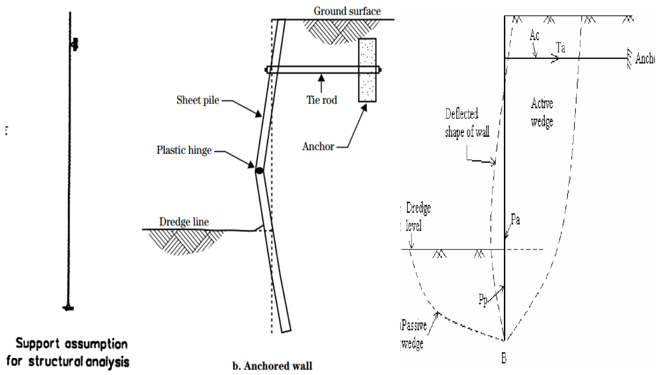
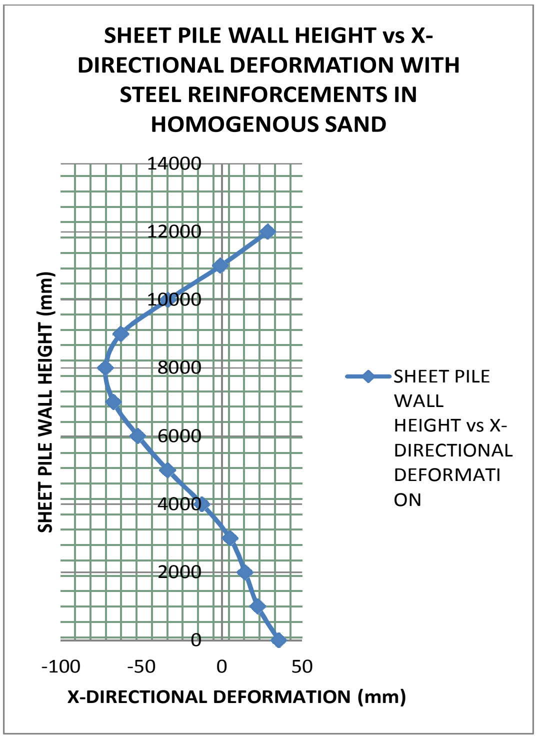


Figure 3.4: Deformation assumptions of anchored wall

The FEA deformation of the sheet pile wall shows a similar response as those assumed in the conventional design method, with contributions of the soil preventing the total failure of the wall, hence imposing contact interaction between the two materials. The deformation of the wall at the point of anchor i.e 1000mm from the top of the wall shows effective anchorage contribution in preventing failure by keeping the wall intact in position.

The movement of the wall towards the retained soil from the toe to the dredgeline level indicates the pasive condition of the wall whereby the passive effect in achieving stabilty is more pronounced. The outward deflection of the wall away from the retained soil gives an indication of the ative conditions behind the wall.

The deformed response shown in Figure 3.5illustrates that most of the wall height is in active condition while the anchor restraint pushing the back inwards to prevent failure.



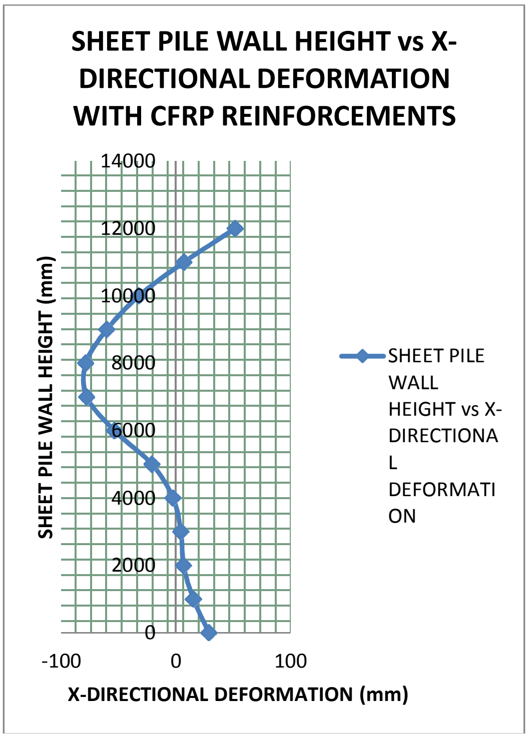


Figure 3.5: Horizontal deformation of anchored sheet pile with steel & CFRP reinforcements

As shown in Figure 3.5, it is evident that the deformation of the anchored sheet pile is similar in both cases, except that the wall reinforced with CFRP exhibits irregular defomation pattern compared to steel reinforced wall.

3.3 Effects of Cohesion / Angle of Friction

The common practice in the design of sheet piles embedded in soil with small cohesion and large angle of friction value is to assume the soil as evenly cohesionless. This is the approach used in the conventional design method which prominently exists as a design method for clayey or sandy soil. While this simplified approach is acceptable under certain conditions, the effects of varying values of cohesion and angle of internal friction can be outsized in other instances as the case study under consideration (see Table 1). In Figure 3.6 shown below, some of these effects are illustrated.

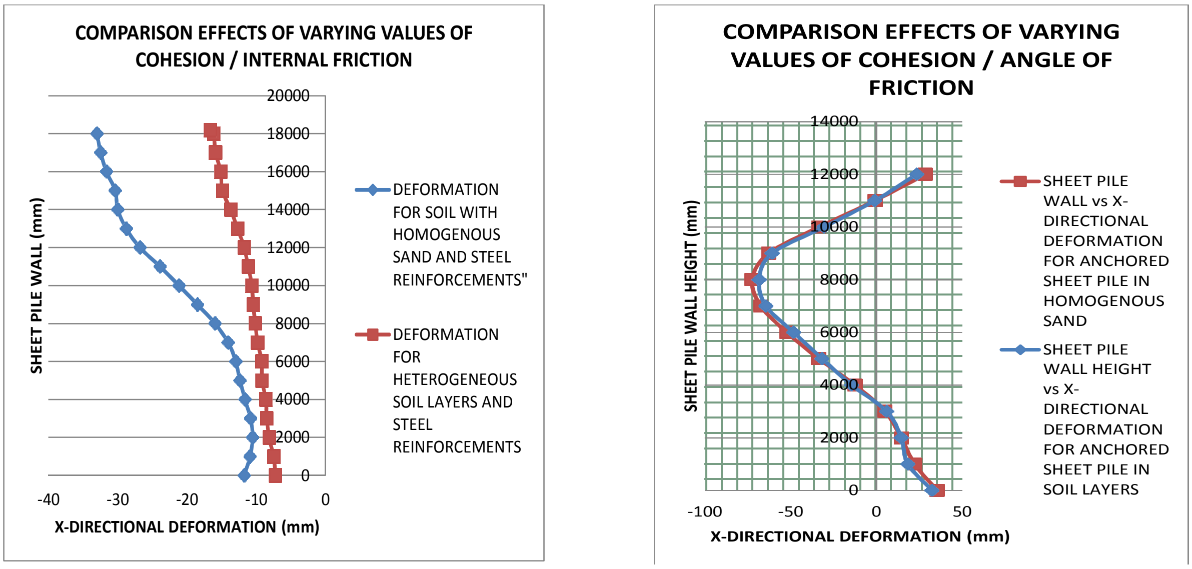


Figure3.6: Comparison Effects of varying values of Cohesion / Internal Friction

As seen in Figure 3.6, the deformations of the cantilevered wall embedded in homogenous and heterogeneous soils are 31.833mm and 16.663mm respectively. The deformation factor here is in the other of 2. Hence, the assumed homogeneous sand condition results in overestimation of deformation. This is a clear pitfall of conventional design approach when compare to FEA on two distinct soil types. However, for the anchored walls, no clear difference exists in the deformation response and magnitude.

Typical stress and strain distributions along the height of the sheet pile wall over time to capture the nonlinearity response under time-based incremental loading are presented in Figure 3.7.

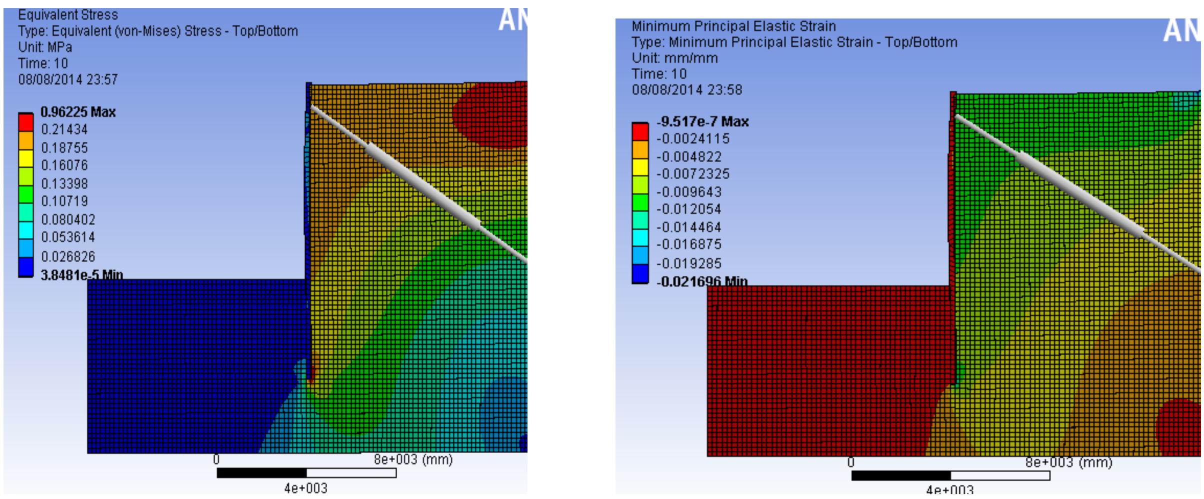


Figure 3.7: Stress and Strain distributions along the sheet-pile length

4.0 CONCLUSIONS

From the above analysis and discussions, the following conclusions can be drawn:

- For all test specimens in this numerical study, in addition to the rotational movement of the embedded walls, translational motion about the toe of the walls was also observed. Such phenomenon is ingored and difficult to detect in the conventional limit equilibrum design approach.

- Both rotational and translational deformations are generally higher in homogeneous soil compared to heterogeneous soil. Hence, the assumed homogeneous sand condition used in conventional design approach gives rise to overestimation of deformation. This is a clear pitfall of conventional design approach when compare to FEA on two distinct soil types.
- The deformation of the anchored sheet pile is similar in both homogeneous and heterogeneous soil, except that the wall reinforced with CFRP exhibits irregular defomation pattern compared to steel reinforced wall.

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